Comparative Study on Multiple Three-Phase Permanent Magnet Motors in Fault Tolerant Electric Power Steering Application

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Abstract

Electric power steering (EPS) is a safety-critical compoment in modern vehicles. Along with the rise of connected and autonomous vehicles, an EPS system needs to achieve fail-operational in the event of a fault. Thus, it mandates redundant architecture to increase reliability and performance in steering function. By providing steering assistance, a multi three-phase electric motor is a fault-tolerant solution for a functional safety architecture. This paper presents a comparative study between dual and triple three-phase interior permanent magnet (IPM) motors with single layer winding. The corresponding electromagnetic performance is predicted considering the influence of rotor pole numbers. The detailed comparison is made between dual three-phase 12 stator-slot/10 rotor-pole (12s10p) and triple three-phase 18 stator-slot/10 rotor-pole (18s10p) IPMs in both healthy and fault modes. Primary experiemental results are presented in the dual three-phase IPM motor.

1 Introduction

With the rapid development in connected and autonomous vehicles, the corresponding safety requirements have evolved from fail-safe to fail-operational which calls for high degree of fault tolerance [1-2]. As one of the essential actuators in autonomous vehicles, electric power steering (EPS) needs to provide continuous functionality during driving and parking even in the event of a system malfunction. In this context, a motor drive control unit based on a motor with multiple three-phase elements becomes an effective solution for increasing system reliability and fault tolerance for the EPS application [3-6]. The Denso corporation has reported its 2-drive motor control unit using a 60 stator-slot/10 rotor-pole (60s10p) dual three-phase interior permanent magnet (IPM) motor with distributed winding for EPS systems, which provides half of the normal assisting torque when a malfunction occurs in one set of three-phase system [3]. The performance of the dual three-phase PM motors with different rotor topologies and winding layouts was evaluated in [4-5], concluding that IPM motor has a good fault tolerant capability in terms limiting short-circuit current without too much reduction in shaft torque. A comparative study was presented considering six-phase motor topologies looking at the relative merits of surface-mount permanent (SPM), IPM and induction machines (IM), showing that the IPM is the better candidate for EPS applications demanding high torque density [6].
Building on previous research, this paper presents a comparative study between IPM machines with multiple three-phase elements in one stator housing, i.e. equipped with dual and triple three-phase winding as shown in Fig. 1. In order to achieve physical, electromagnetic and thermal separation between the phases [7], tooth coils are wounded on alternate stator teeth (single layer concentrated winding) in IPM machines. This paper focuses on the design aspects of multiple three-phase machine in EPS motor, particularly in electromagnetic performance of the machine. This paper is organized as follows. The investigation of multiple IPMs are modelled with 2D finite element analysis (FEA) in Motor-CAD by considering the influence of different stator/rotor pole number combinations in section 2. The detailed healthy and faulty performance is compared and analysed between dual three-phase 12s10p and triple three-phase 18s10p IPM in section 3. Primary experiements are conducted in the dual three-phase 12s10p IPM in section 4. General conclusion is given in section 5.

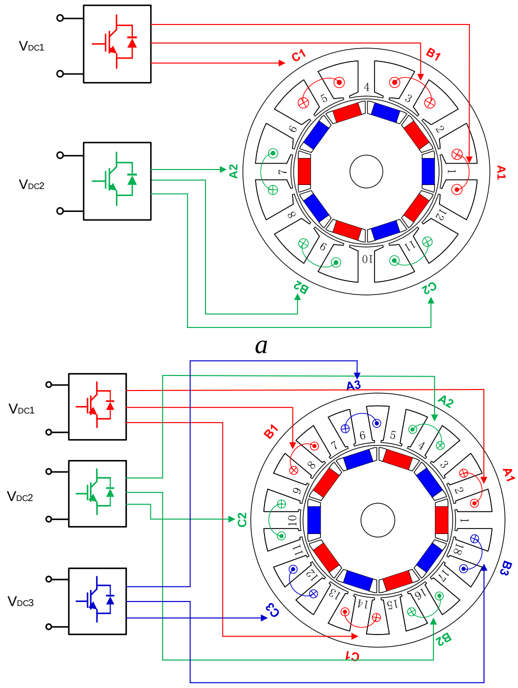


Fig. 1 Multiple three-phase EPS motor drive. (a) Dual three-phase 12s10p IPM motor and (b) triple three-phase 18s10p IPM motor.

2. Influence of different rotor pole numbers in multiple three-phase IPMs

The electromagnetic performance is investigated in multiple three-phase machines with single layer tooth winding. The minimal stator slot number N_s can be used for a dual three-phase IPM is 12 while it is 18 for a triple three-phase IPM. A higher stator slot number is not recommended for the given space envelope since it will reduce the available slot area and increase the difficulties in winding process as a result of the very small slots. The range of rotor pole numbers is limited from 4 to 20 in order to achieve the maximum flux linkage per pole. The influence of rotor pole numbers in torque performance is revealed under the conditions as listed Table 1.

Table 1 Parametric constrains in dual and triple three-phase IPMs.

Parameter	Symbol	Unit	Value
Stator outer diameter	D_{os}	mm	90
Lamination active length	L_a	mm	95
Air-gap clearance	g	mm	1
Packing factor	k_p	-	0.40
DC link voltage	U_{dc}	V	12
Maximum inverter current (peak)	I_{dc}	A	100
Excitation current (rms)	I_{rms}	A	50
Magnet weight	W_{PM}	kg	0.30
Base speed	n_{base}	rpm	1650
Number of turns per tooth coil	N_c	-	8

Under the same drive conditions, it is observed that 12s10p and 18s10p IPMs have higher shaft torque and lower torque ripple than other candidate options as shown in Fig. 2. It is also evident that triple three-phase IPMs, especially for 18s/(10,14)p configuration, can have a higher torque output and significant lower torque ripple than dual three-phase IPMs. High torque density is always preferred for an electric motor since it brings the advantages in terms of high efficiency with lighter weight. Low torque ripple is highly desirable for the EPS application since it increases smoothness in steering and enhances the steering experience for the driver. In the next section, a detailed electromagnetic performance comparison between 12s10p and 18s10p IPMs is made, which is referred as dual three-phase and triple three-phase motor respectively.

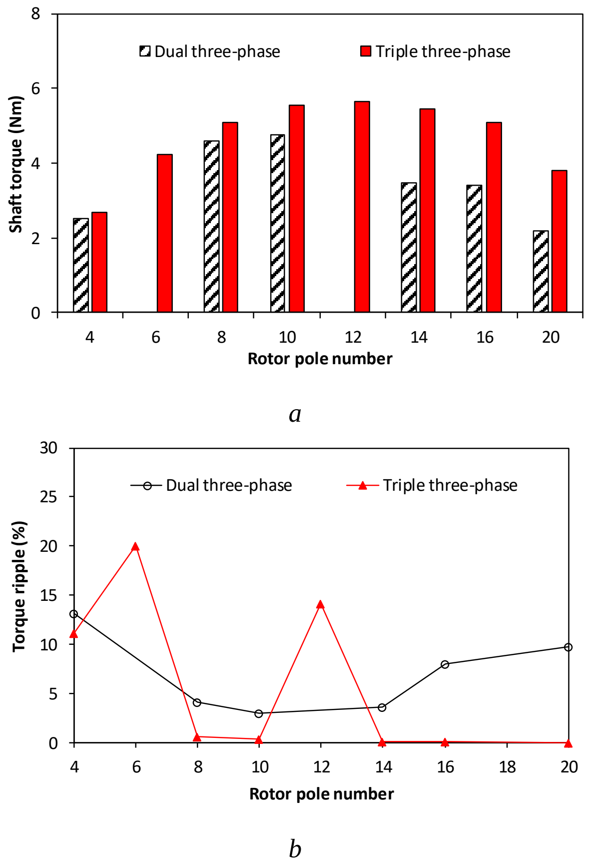
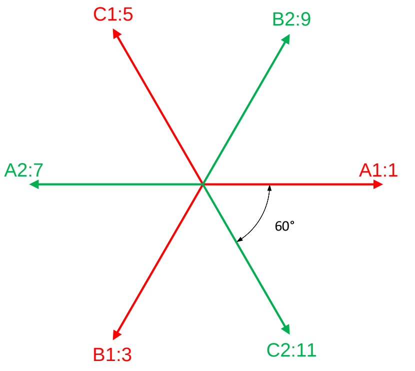


Fig. 2 Comparison of torque performance between dual and triple three-phase IPMs. (a) Average torque against feasible rotor pole numbers and (b) torque ripple against feasible rotor pole numbers.

3 Performance comparison between multiple three-phase IPMs

3.1 Healthy mode

By employing single layer winding in multiple three-phase IPMs, coils are wounded in alternate stator teeth as indicated by the phase vectors in Fig. 3. In the dual three-phase IPM there is a 60 electrical degree phase shift between the two sets of three-phase windings while in the triple three-phase IPM has 20 electrical degree phase shift between three set of three-phase windings. Thanks to the use of a single layer winding, the open-circuit flux pattern of each coil is concentrated and physically separated by the middle tooth as shown in Fig. 4. This winding arrangement leads to an increase in self-inductance and a reduction in the mutual coupling between the phases [7], which is shown in Fig. 5. The ratio between the mutual- and self-inductance in dual three-phase is 8.23% and it is only 4.26% in triple three-phase IPM. In the case of a short-circuit fault occurs in a winding, the single layer arrangement has advantage of limiting the fault locally in one coil with little influence on the other coils. In addition, single layer concentrated windings have shorter end-winding lengths than distributed windings, which increases motor manufacturability of mass production.



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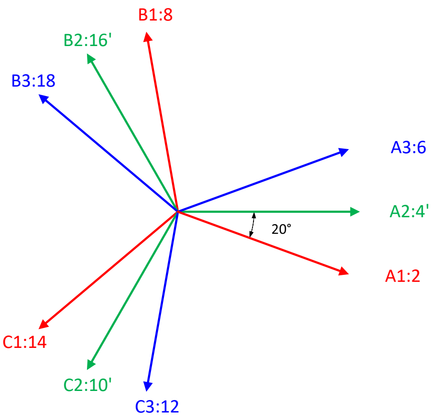

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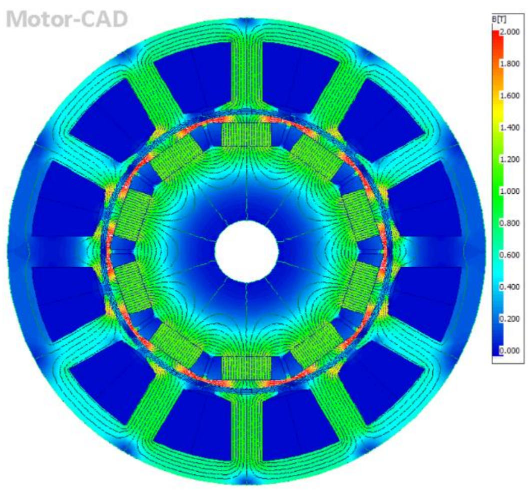
Fig. 3 Phase vectors for single layer winding layout in (a) dual three-phase 12s10p IPM and (b) triple three-phase 18s10p IPM.



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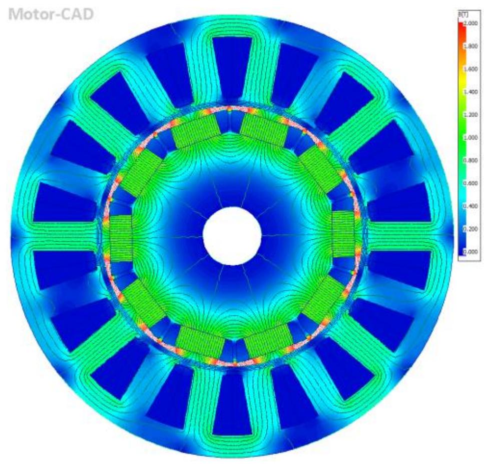

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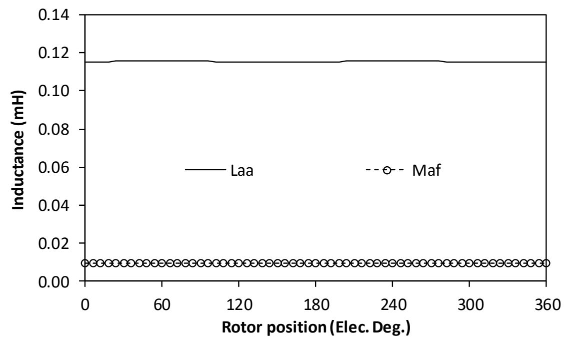
Fig. 4 Flux line and flux density distribution for multiple three-phase IPMs under open-circuit. (a) Dual three-phase IPM and (b) triple three-phase IPM.



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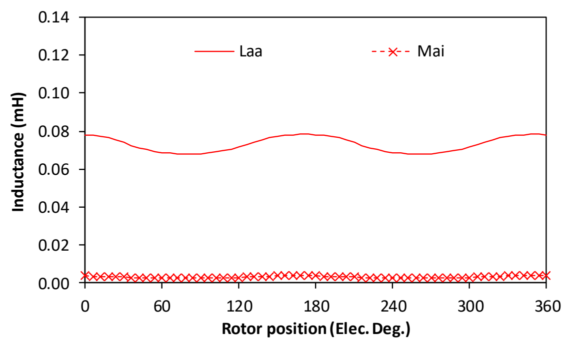

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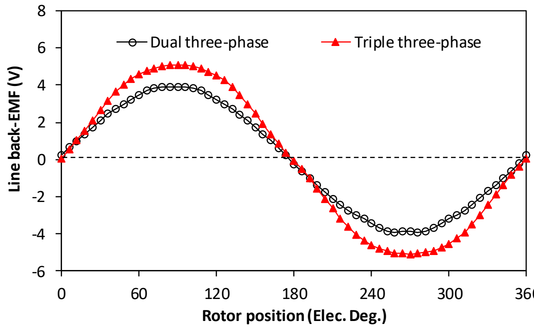
Fig. 5 Self- and mutual- inductance profile for (a) dual three-phase IPM and (b) triple three-phase IPM.

The line back-EMF are predicted for multiple three-phase IPMs at 1650 rpm as shown in Fig. 6. It is seen that triple three-phase IPM has 32.9% higher fundamental value than dual three-phase IPM, which is correlated with higher shaft torque in triple three-phase IPM.



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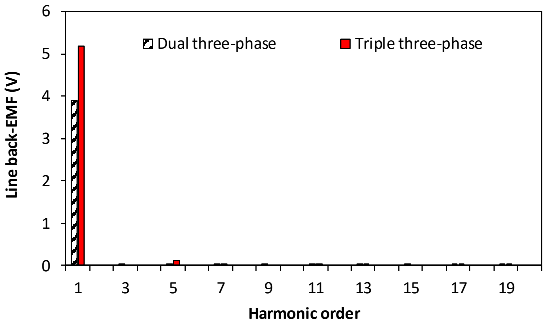

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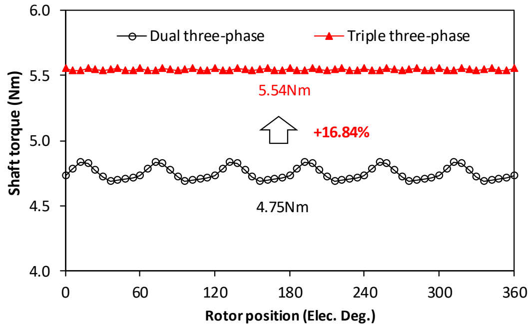
Fig. 6 Back-EMF for multiple three-phase IPMs at 1650rpm. (a) Waveforms and (b) spectra.



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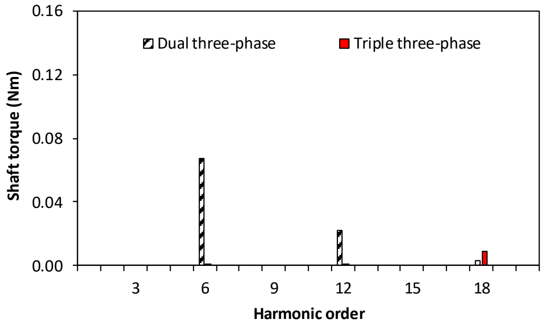

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Fig. 7 On-load torque performance for multiple three-phase IPMs in healthy operation. (a) Shaft torque waveforms and (b) spectra without DC components.

During healthy operation, i.e. with balanced multiple three-phase current excitation, on-load torque waveforms are illustrated in Fig. 7(a). The average value of shaft torque in the triple three-phase IPM is increased by 16.84% in comparison with the dual three-phase IPM with the same amplitude of multiphase excitation currents (I_{rms} = 50 A). This phenomenon can also be interpreted as the total maximum current rating in triple three-phase inverter can be reduced compared to that in the dual three-phase machine for the same motor torque, even allowing for the increased number of phases and reduced phase currents. Inverter downsize leads to the reduction in weight and cost in chip devices [3]. Another advantage with triple three-phase IPM is that the torque ripple is reduced from 3.05% to 0.33% which is mainly due to the elimination of 6th and 12th order harmonics as shown in Fig. 7(b). An EPS is ought to support large amount torque at low speed steering manuover, i.e. parking, and remains low torque at high speed to ensure driving stability. Therefore, flux-weakening performance is vital for an EPS motor, which is shown in Fig. 8. It depicts that tipple three-phase has higher and wider constant torque region (7.84 Nm with n_{base} at 2000 rpm) than dual three-phase IPM (6.44 Nm with n_{base} at 1800 rpm) under the same drive condition (U_{dc} = 12V and I_{dc} = 100 A). Meanwhile, triple three-phase (1.84 kW) delivers 36.3% higher power than dual three-phase IPM (1.35 kW0 in the constant power region.

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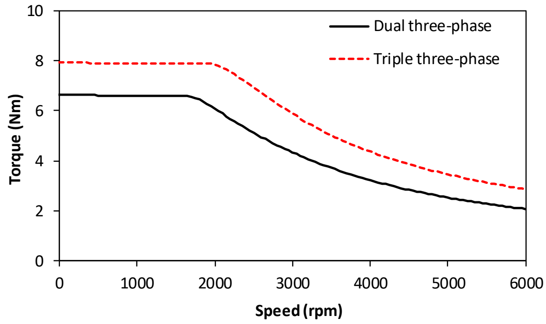

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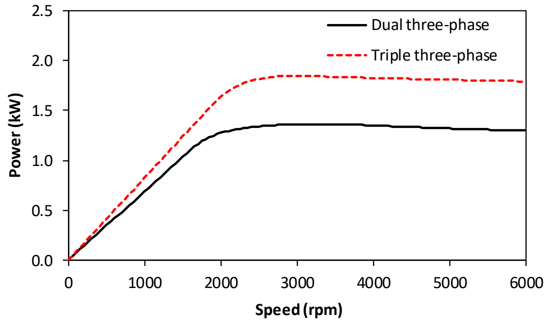

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Fig. 8 Flux-weakening performance for multiple three-phase IPMs. (a) Torque versus speed and (b) power versus speed.

3.2 Faulty mode

The most attractive feature in multiple three-phase motors is that the motor has the capability to operate continuously, albeit with degraded performance, in faulty conditions. The torque behaviour of multiple three-phase IPMs with steady state current excitation has been investigated with one set of three-phase windings open-circuited (OC) in Table 2. It has been found that the output torque losses, as expected, are 50% in dual three-phase and 33.3% in triple three-phase IPM. In other words, the current rating in EPS system needs to be overrated 2 times in dual three-phase system while 1.5 times in triple three-phase system as shown in Fig. 9. However, torque ripple generally increases with the increase of electrical loading. The level of torque ripple in OC faulty condition for dual and triple three-phase IPMs is within 10% which has less influence for a rack-type EPS system.

Table 2 Comparison of healthy and OC fault performance for multiple three-phase IPMs.

Operating conditions	**I_{rms} = 50 A**	
	Average torque (Nm)	**Torque ripple (%)**
Dual three-phase healthy	4.75	3.05
Dual three-phase OC	2.38	3.32
Triple three-phase healthy	5.54	0.33
Triple three-phase OC	3.69	6.32

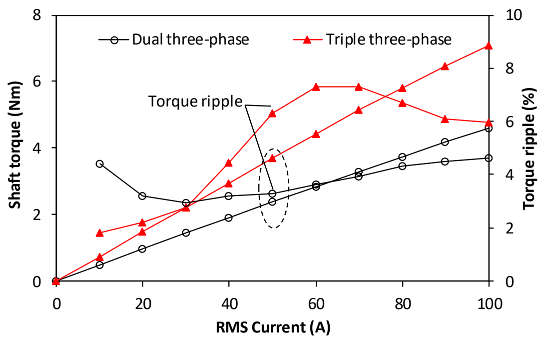


Fig. 9 Shaft torque and torque ripple against different current under OC faulty condition.

Based on the comparative study in OC faulty conditions, it shows that triple three-phase IPM has better electromagnetic performance than dual three-phase. Considering the case of a symmetrical three-phase short-circuit (SC) fault occurring in one set of three-phase winding while the rest of phases are supplied normally, the resulting SC current has been calculated in the faulty winding under different rotor speeds as shown in Fig. 10(a). It shows that the SC current in triple three-phase IPM is about 10.28% lower than in dual three-phase one, which reduces the risk of current overload in power electronic devices. Consequently, the unwanted braking torque in triple three-phase IPM is much lower than dual three-phase winding especially at low speed condition as shown in Fig. 10(b).

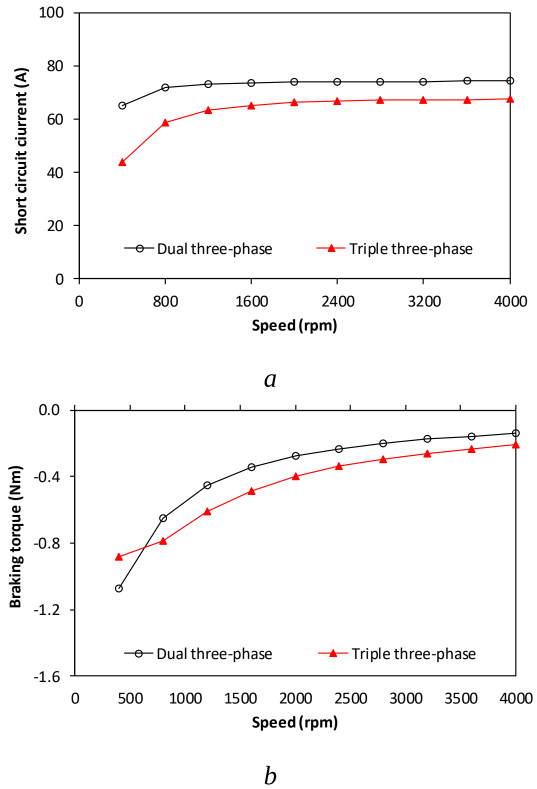


Fig. 10 Steady state SC current and braking torque for multiple three-phase IPMs under a three-phase SC fault. (a) SC current under different speed and (b) braking torque under different speed.

4 Experimental results

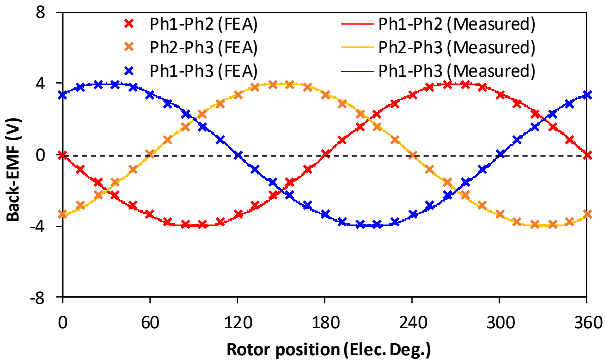
In order to verify the electromagnetic study of multiple three-phase IPM motor, a dual three-phase IPM prototype motor is firstly built according to the parameters in Table 1. The stator assembly is shown is Fig. 11(a), in which there are six tooth coils with two independent star points. Three step skewing is applied to the rotor with 6 mechanical degree with respect to each segment in order to reduce torque ripple as shown in Fig. 11(b). The motor characteristic including line to line resistance and inductance are measured in Table 3. The difference between measurement and prediction is due to longer cable leads and end-winding effect. The open-circuit back-EMF measurement is conducted in one set of three-phase winding and the waveforms at 1650 rpm is shown in Fig. 12. The measurement of three phase line back EMF agrees well with FEA prediction not only at 1650 rpm but also in the fundamental values against different motor speeds.

a *b*

Fig. 11 Dual three-phase 12s10p IPM prototype components before assembly. (a) Stator and (b) 1/3 of the rotor segment.

Table 3 Machine characteristics of dual three-phase IPMs.

	FEA predicted	Measured
L-L resistance (Ohm)	0.0094	0.0142
L-L inductance (μH @ 1kHz)	143.7	160.1



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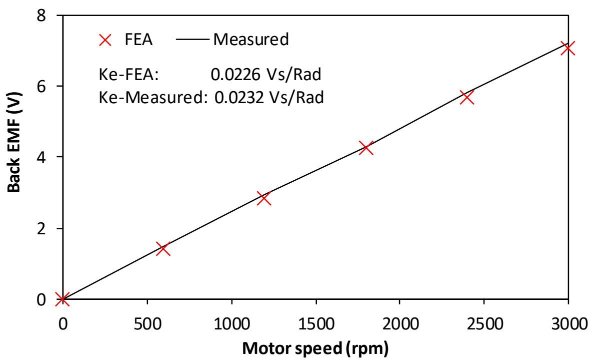

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Fig. 12 Line back-EMF measurement. (a) Waveforms at 1650 rpm and (b) fundamental back-EMF versus different speed.

5 Conclusions

In this paper, the electromagnetic performance of dual and triple three-phase IPMs have been compared. Considering the influence of stator and rotor pole number combinations, 12s10p IPM was selected as the candidate in dual three-phase configuration while 18s10p IPM is selected as the candidate in triple three-phase configuration for high shaft torque and low torque ripple. The investigation shows that triple three-phase 18s10p IPM has higher shaft torque and significant lower torque ripple than its counterpart under the same healthy mode. Furthermore, the investigation in faulty modes shows that the triple three-phase machine has better advantages in both open- and short-circuit conditions, which is better for a fail-operational EPS system. A dual three-phase 12s10p IPM prototype is manufactured. Its corresponding back-EMF characteristics are measured to vadilate the FEA calculation.

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